ADVANCES IN COHERENT SYNCHROTRON RADIATION AT THE CANADIAN LIGHT SOURCE

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While good sources of radiation are available for most of the electromagnetic spectrum, an intense broadband source for the terahertz region is still lacking. Synchrotrons have offered a source of radiation for much of the electromagnetic spectrum; however, in normal operation they do not provide an intense source in the terahertz region. Despite this, a synchrotron can be used as an excellent source of terahertz radiation by modifying the operating conditions of the storage ring to produce coherent synchrotron radiation (CSR). Production of CSR has been demonstrated at a number of synchrotrons worldwide [1]. At the Canadian Light Source, research is being performed into the production, the physics, and the application of CSR.

THE BASIC PHYSICS OF COHERENT SYNCHROTRON RADIATION PRODUCTION

Electrons in a synchrotron travel in discrete groups called bunches. Normally these bunches are about 10 mm in length. Under normal operating conditions, the radiation power produced by one bunch goes as:

$$P = \frac{2a^2 Ne^2}{3c^3} \quad (1)$$

where $a$ is acceleration, $N$ is the number of electrons per bunch, $e$ is the charge on an electron and $c$ is the speed of light. By contrast, if the bunch length is smaller than the wavelength of the radiation, the bunch behaves like a “fat electron” with charge $Ne$, and the corresponding radiation is very nearly coherent in phase. In this case the radiated power goes as:

$$P = \frac{2a^2 (Ne)^2}{3c^3} \quad (2)$$

In short, the power is no longer linear with the number of electrons, but quadratic, which in favourable cases can lead to a factor of $10^6$ increase in power.

Unfortunately it is generally not practical to reduce the physical bunch length to the degree necessary to truly achieve this. Instead, in order to achieve the CSR condition, we operate in one of two bunch modes: continuous or bursting. The continuous mode is achieved by filling each bunch (up to 210 in total) to roughly 50 microamperes, and then relying on the radiation impedance to deform the bunch from its normal Gaussian distribution to a “shark fin” profile (see Figure 1). The high frequency part of the “shark fin” distribution acts, in effect, as a short bunch, which generates the CSR. Although the power increase is not as high as predicted above, gains of $10^3$-$10^4$ can be achieved. Continuous mode operation has been achieved at the CLS, because of the naturally smaller bunch length at lower energies, this was done operating at 1.5 GeV rather than 2.9 GeV (the normal operating energy of the CLS).

The mechanism of bursting mode is somewhat more complicated to describe. The bunches are filled to about

![Graph of “Shark fin” electron density along the longitudinal axis, where the red box roughly delineates the high frequency component of the electron density.](image)
10 mA each, and random noise within the bunch distribution is sufficient to seed the start of the bursting process. This noise acts like a very small “micro-bunch” within the larger bunch. Figure 2 illustrates the mechanism by which these micro-bunches are enhanced. For the sake of simplicity let’s assume that the micro-bunch contains 2 electrons moving through a bending magnet. The trailing electron radiates a transverse field tangential to the path of the electron. Since the electron’s path is curved, the transverse field catches up with the leading electron. Because the leading electron is no longer travelling parallel to the propagation vector of the field, a component of the electric field is projected parallel to the motion of this electron, and it gains energy. The net result is that the trailing electron loses energy and the leading electron gains energy, so they enter slightly smaller and larger orbits respectively. The leading electron will therefore take slightly longer to circle the ring than the trailing electron, and the electrons will appear to move closer together longitudinally. Extrapolating now to a multi-electron bunch, the resulting micro-bunch radiates more power, creating a runaway situation which leads to progressively smaller micro-bunches producing even stronger CSR. Eventually the process leads to a longitudinal beam instability which drives the bursting. Following the longitudinal burst, radiative damping leads to a reformation of the original conditions, and the process starts again. Thus, the bunch behaves like a repeating shotgun, with the time between firing being in the sub-millisecond domain. Bursting mode operation has been achieved at the CLS at both 2.9 and 1.5 GeV. Total

\[ f_s = \text{const } a^{\frac{1}{5}} \]  

The momentum compaction is a constant which depends on the optical setup of the synchrotron. It defines the relationship between the relative energy spread of the electrons in the bunch and the longitudinal spread of the electrons (\( \Delta L \)) over the average length of one complete orbit of the ring (\( L_0 \)), or

\[ \frac{\Delta L}{L_0} = a^2 \delta \]  

Beyond the production of CSR, research is being performed into both the physics and the application of CSR. In the following paragraphs we will discuss one example of each of these avenues of research: Inter-bunch interference (also known as super-radiance) and Photoacoustic spectroscopy using CSR.

**MULTI-BUNCH INTERFERENCE**

The power spectrum from an electron synchrotron derives from the accumulation of light pulses from successive bunches. For sufficiently short bunches, a unique phase relation exists between successive fields, and a coherency is established between bunches. This bunch-to-bunch coherency manifests itself in an interferogram as a periodic sequence of patterns similar to the familiar center-burst pattern. The physics behind this phenomenon has been described in Jackson’s book[2], and bunch-bunch interference was observed at low resolution by Shibata et al.[3] using a linac. The CLS was the first to report the observation of this phenomenon in a Storage Ring and the first to observe it at high resolution[4]. CSR was produced in the continuous mode by operating the CLS synchrotron at 1.5 GeV, with the momentum compaction adjusted to produce a bunch length of a few picoseconds. Total

For practical reasons the synchrotron frequency is usually measured, rather than the bunch length. The bunch length is related to the synchrotron frequency by the following equation:

\[ \sigma = \frac{a}{2\pi f_s} \delta \]  

where \( \sigma \) is the bunch length, \( a \) is the momentum compaction, \( f_s \) is the synchrotron frequency and \( \delta \) is the relative energy spread. Note that the synchrotron frequency is related to the
beam current was about 4.9 mA, distributed over 210 bunches. Spectra were collected on a Bruker IFS 125 HR spectrometer, using a 75 μm Mylar beam splitter and Infrared Labs Si Bolometer. A 12.5 mm aperture was used, with gain at 200X, a scanner velocity of 60 kHz, and a resolution of 0.002 cm⁻¹.

The first features one may notice in the interferogram shown in Figure 4 are the centerburst-like features spaced at 600 mm intervals, from 600 to 4200 mm pathlength difference. These features are due to interference of the coherent light emitted by one bunch with that of its nearest neighbour, or the bunch once removed, or twice removed, etc., up to seven times, respectively. Note that this interference demands a well-defined phase relationship between the light emitted by all bunches.

The Fourier transform of the interferogram, shown in Figure 5, displays the sharp spectral features that result from these correlations. These features are more readily observed in the expanded 6.0-6.2 cm⁻¹ region shown in the inset of this figure. The fine structure in these figures can be explained by considering that the intensity of CSR from \( N_b \) successive bunches is given by

\[
I(\lambda) = N_c^2 \cdot f(\lambda) \cdot B(\lambda)
\]  
(6)

where \( f(\lambda) \) is a bunch length dependent form factor, \( N_c \) is the electron population of each bunch and \( B(\lambda) \) is

\[
B(\lambda) = \left[ \frac{\sin \left( \frac{N_c \pi d}{\lambda} \right)}{\sin \left( \frac{\pi d}{\lambda} \right)} \right]^2
\]  
(7)

with \( d \) the bunch separation (~600 mm). The envelope defined by eq. (7) is shown in black in the insert, with arbitrary normalization.

The ultimate result of this is that the while the average power still goes as \( N_b(N_c)^2 \), it is now concentrated in a series of high quality-factor peaks, where the peak power varies as \( N_b(N_c)^2 \) with \( N_b \) being the number of bunches.

**PHOTOACOUSTIC SPECTROSCOPY USING CSR**

While the physics behind CSR is important and interesting, the CLS as a user facility is also concerned about the practical application of the radiation it produces. There are many applications for CSR: one innovative use of this radiation is as a source for Photoacoustic spectroscopy (PAS). This application was first demonstrated at the CLS [5].

Fourier Transform Infrared Photoacoustic Spectroscopy is a well established technique, which obviates the need for traditional sample preparation methods and allows for the study of solid and/or opaque samples. Furthermore heterogeneous and layered samples can be characterized using PAS depth profiling techniques [6]. PAS can simply be described as follows: modulated radiation of a wavelength that coincides with a vibrational mode of the sample impinges on the sample and is then absorbed. The molecules of the sample are thus raised to a vibrationally excited state. When the molecule relaxes back to its ground state the energy is dissipated as heat, creating a thermal wave in the sample. This heat wave is then transferred to a carrier gas which in turn creates a pressure wave. If the modulation occurs at acoustic frequencies, the pressure (sound) wave can be detected using a sensitive microphone.

For the experiments described herein an MTEC PAS cell was used. The gain was set at 2000X and Helium was used as the carrier gas. Spectra were recorded using a Bruker IFS 125 HR spectrometer fitted with a 75 μm Mylar beamsplitter. The aperture was set at 12.5 mm and the scanning frequency was 5 kHz.
Figure 6 compares PAS spectra of carbon black collected using an Hg lamp (black), conventional synchrotron radiation with 220 mA in the ring (blue) and CSR with 10.9 mA in the ring and $f_s$ set to 5.5 kHz (red). It is immediately evident that useful spectra are not obtained using either the Hg lamp or normal synchrotron radiation, while an excellent spectrum is observed using CSR.

While the result for carbon black demonstrates the advantage of CSR PAS very well, it lacks the spectral features that are generally of interest to spectroscopists. Instead α-lactose monohydrate (milk sugar) was chosen as a test molecule for this study: this material is known to exhibit a strong absorption band at $\sim 18$ cm$^{-1}$ [7,8]. This substance was obtained from Sigma Aldrich and used without further preparation.

The red trace in Figure 7 shows a photoacoustic spectrum of α-lactose monohydrate obtained at 2 cm$^{-1}$ resolution. CSR was produced with a current of 10.9 mA divided between two bunches; the synchrotron frequency was 5.2 kHz. The expected peak at $\sim 18$ cm$^{-1}$ can clearly be observed in this spectrum, demonstrating the utility of this technique.

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REFERENCES